

$\Delta F = 2$ Observables and Fine-Tuning in a Custodially Protected Warped Extra Dimension

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based on: MB, BURAS, DULING, GORI, WEILER, 0809.1073

$\Delta F = 2$ in Warped Extra Dimensions

many analyses in the existing literature

BURDMAN, HEP-PH/0205329, HEP-PH/0310144; AGASHE, PEREZ, SONI, HEP-PH/0408134; MOREAU, SILVA-MARCOS, HEP-PH/0602155;
CHANG, KIM, SONG, HEP-PH/0607313; CSAKI, FALKOWSKI, WEILER,
0804.1954; ...

What is new in BBDGW?

First complete analysis of $\Delta F = 2$ processes

- within the **custodially protected RS model**
- including simultaneously **all $\Delta F = 2$ operators**
- performing **RG-running at the NLO level**
- including both **strong and electroweak gauge boson contributions**
- considering **all interesting $\Delta F = 2$ observables simultaneously**
- analysing **fine-tuning** in flavour physics

Main Messages from BBDGW

- ① confirmation of **generic bound $M_{KK} \gtrsim 20 \text{ TeV}$ from ε_K**

CSAKI, FALKOWSKI, WEILER, 0804.1954

- ② also for $M_{KK} \gtrsim (2 - 3) \text{ TeV}$ **agreement with ε_K possible without relevant fine-tuning**

- ③ ΔM_K and ε_K are governed by **KK gluon contributions**

- ④ in $B_{d,s} - \bar{B}_{d,s}$ **electroweak KK modes** equally important

- ⑤ **custodial protection** of $Z b_L \bar{b}_L$ efficiently suppresses all **flavour changing $Z d_L^i \bar{d}_L^j$ couplings**

- ⑥ possible **tensions in the SM** ($\varepsilon_K, S_{\psi K_S}, \dots$) can be **solved**

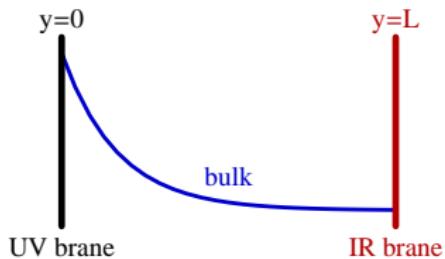
- ⑦ **$S_{\psi\phi}$ and A_{SL}^s can be large**

The basic RS Set-up

5D spacetime with **warped** metric:

RANDALL, SUNDRUM, HEP-PH/9905221

$$ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2, \quad 0 \leq y \leq L$$



- **fermions and gauge bosons** live in the bulk
- **Higgs** localised on IR brane

CHANG ET AL., HEP-PH/9912498

GROSSMAN, NEUBERT, HEP-PH/9912408

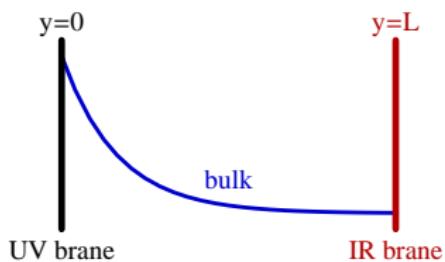
GHERGHETTA, POMAROL, HEP-PH/0003129

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- energy scales suppressed by **warp factor** e^{-ky}
→ **natural** explanation of **gauge hierarchy** problem
- **Kaluza-Klein (KK) excitations** live close to the IR brane

Constraints from EW Precision Tests

S parameter: $M_{KK} \gtrsim (2-3) \text{ TeV}$ AGASHE ET AL., HEP-PH/0308036

T parameter:

- without protection: $M_{KK} \gtrsim 10 \text{ TeV}$

(may be softened by heavy Higgs)

CASAGRANDE ET AL., 0807.4937
BARBIERI ET AL., HEP-PH/0603188, ...)

- with **custodially enlarged gauge symmetry** → ✓

AGASHE ET AL., HEP-PH/0308036; CSAKI ET AL., HEP-PH/0308038

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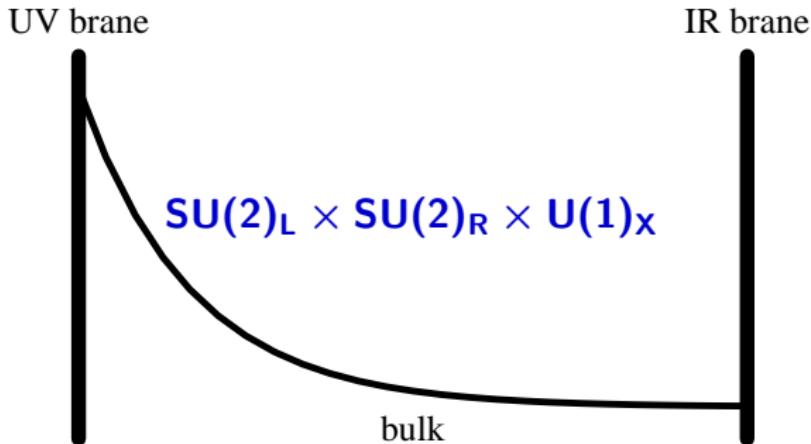
AGASHE ET AL., HEP-PH/0308036; CSAKI ET AL., HEP-PH/0308038

anomalous $Z b_L \bar{b}_L$ coupling: (exp.: $\lesssim 5 \cdot 10^{-3}$)

- corrections arise naturally at the $-(1-2)\%$ level
- protection by **discrete $SU(2)_L \leftrightarrow SU(2)_R$ symmetry** ✓
→ enlarged fermion representations

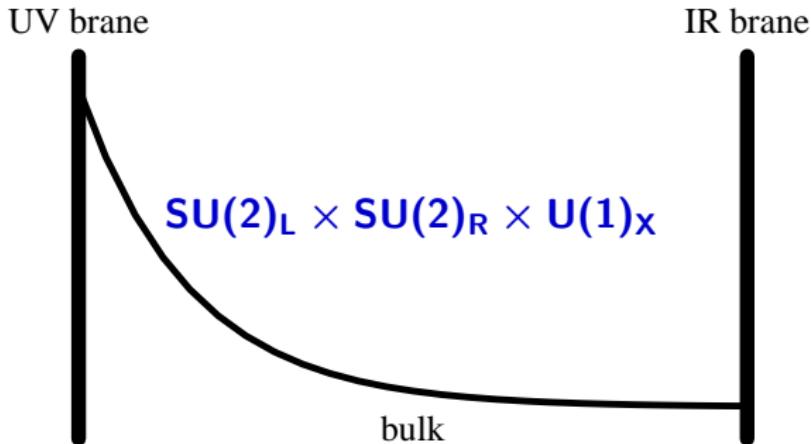
AGASHE ET AL., HEP-PH/0605341; CONTINO ET AL., HEP-PH/0612048
CARENA ET AL., HEP-PH/0607106

A Realistic Model in the Reach of LHC



+ ($L \leftrightarrow R$)-symmetric fermion representations

A Realistic Model in the Reach of LHC



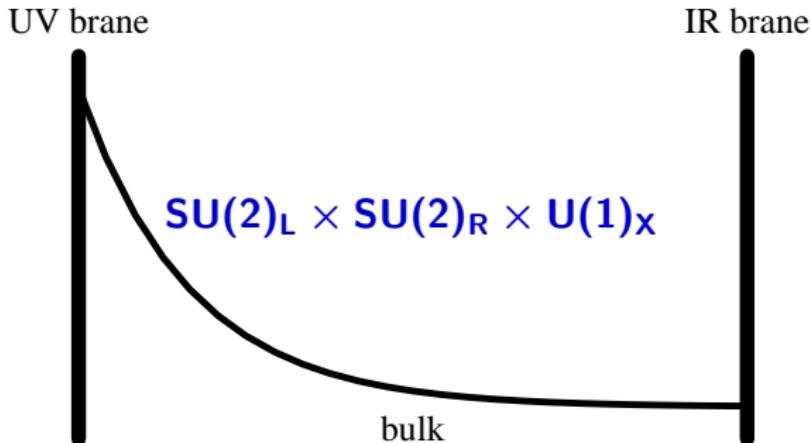
$$SU(2)_R \times U(1)_X \rightarrow U(1)_Y$$

by boundary conditions

+ $(L \leftrightarrow R)$ -symmetric fermion representations

low energy theory: $SU(2)_L \times U(1)_Y$ in the absence of EWSB

A Realistic Model in the Reach of LHC



$SU(2)_R \times U(1)_X \rightarrow U(1)_Y$
by boundary conditions

$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$
by Higgs VEV

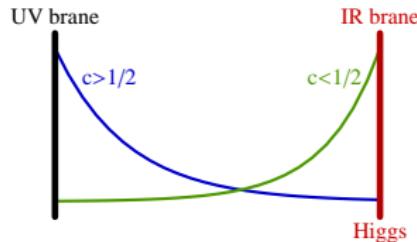
+ $(L \leftrightarrow R)$ -symmetric fermion representations

low energy theory: $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{em}}$

Fermion Localisation and Yukawa Couplings

zero mode profile depends strongly on bulk mass parameter **c**:

$$f^{(0)}(y, c) \propto e^{(\frac{1}{2}-c)ky}$$

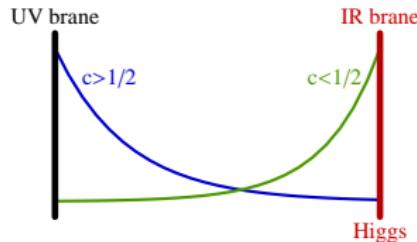


$c > \frac{1}{2}$: localisation around **UV brane**
 $c < \frac{1}{2}$: localisation around **IR brane**

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$c > \frac{1}{2}$: localisation around **UV brane**
 $c < \frac{1}{2}$: localisation around **IR brane**

effective 4D Yukawa couplings: $(Y_{u,d})_{ij} = (\lambda_{u,d})_{ij} f_i^Q f_j^{u,d}$

- $\lambda_{u,d} \sim \mathcal{O}(1)$ anarchic complex 3×3 matrix
- **hierarchical structure** can be naturally generated by exponential suppression of $f^{Q,u,d}$ (fermion profile on IR brane)

Flavour Violation by KK Gauge Bosons

- **KK gauge bosons** localised close to **IR brane**: $g(y) \sim e^{ky}$
- couplings to SM fermions depend on their localisation
- **flavour eigenbasis:**

$$\bar{\psi}_i G_\mu \psi_i \sim -ig^{4D} \gamma_\mu \sqrt{kL} (\mathbf{f}_i^\psi)^2 + \text{const.}$$

flavour-diagonal, but non-universal!

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- rotation to **mass eigenbasis** via $\mathcal{D}_{L,R}$: (estimate for anarchic $\lambda_{u,d}$)

$$\begin{aligned}\bar{d}_L^i G_\mu d_L^j &\sim -ig^{4D} \gamma_\mu \sqrt{kL} \mathbf{f}_i^Q \mathbf{f}_j^Q \\ \bar{d}_R^i G_\mu d_R^j &\sim -ig^{4D} \gamma_\mu \sqrt{kL} \mathbf{f}_i^d \mathbf{f}_j^d\end{aligned}$$

- **tree level FCNCs arise!**
- **protected by RS-GIM mechanism**

AGASHE, PEREZ, SONI, HEP-PH/0408134

Contributions to $\Delta F = 2$

- **KK gluons**

AGASHE, PEREZ, SONI, HEP-PH/0408134
CSAKI, FALKOWSKI, WEILER, 0804.1954; BBDGW

- **KK weak gauge bosons** ($Z_H, Z', A^{(1)}$)

BBDGW

subdominant in $K - \bar{K}$, but **competitive** in $B - \bar{B}$

- **Z boson**

BBDGW

suppressed thanks to custodial protection mechanism
→ extends **custodial protection** to $Z d_L^i \bar{d}_L^j$ couplings

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- generally: **new operators** are induced:

$$\mathcal{Q}_{LL} = (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma_\mu P_L d) \quad \mathcal{Q}_{1LR} = (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma_\mu P_R d)$$

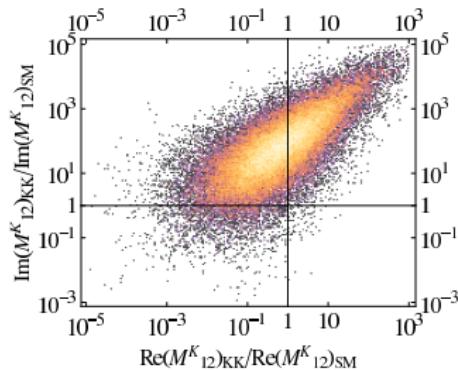
$$\mathcal{Q}_{RR} = (\bar{s}\gamma_\mu P_R d)(\bar{s}\gamma_\mu P_R d) \quad \mathcal{Q}_{2LR} = (\bar{s}P_L d)(\bar{s}P_R d) \quad (*)$$

(*) KK gluons only

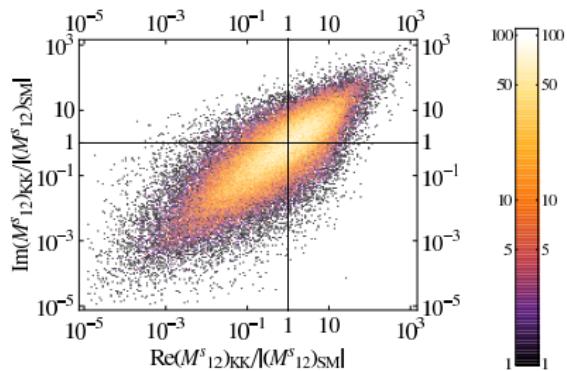
\mathcal{Q}_{LR} : QCD (K and B) and chirally (only K) enhanced!

KK Gauge Boson Contribution to M_{12}^i

$K - \bar{K}$ mixing:



$B_s - \bar{B}_s$ mixing:



$$\begin{aligned}\text{Re}(M_{12}^K)_{\text{KK}} &\sim \text{Re}(M_{12}^K)_{\text{SM}} \\ \text{Im}(M_{12}^K)_{\text{KK}} &\sim 10^2 \text{Im}(M_{12}^K)_{\text{SM}}\end{aligned}$$

generally tension with ϵ_K

CSAKI, FALKOWSKI, WEILER

$$\begin{aligned}|(M_{12}^s)_{\text{KK}}| &\sim |(M_{12}^s)_{\text{SM}}| \\ \text{Arg}(M_{12}^s)_{\text{KK}} &\sim \mathcal{O}(1)\end{aligned}$$

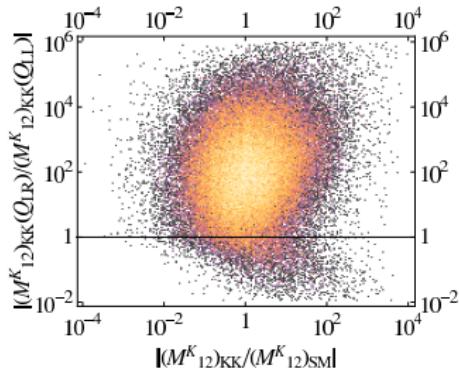
large $S_{\psi\phi}$ expected

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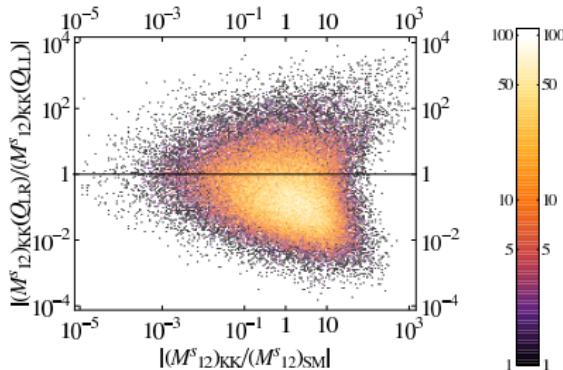
all results for $M_{\text{KK}} \simeq 3 \text{ TeV}$

Operator Competition in $\Delta F = 2$

$K - \bar{K}$ mixing:



$B_s - \bar{B}_s$ mixing:



Q_{LR} dominates
by two orders of magnitude
KK gluons dominant

Q_{LL} and Q_{LR}
are competitive
EW KK modes important

(no chiral LR enhancement in B system)

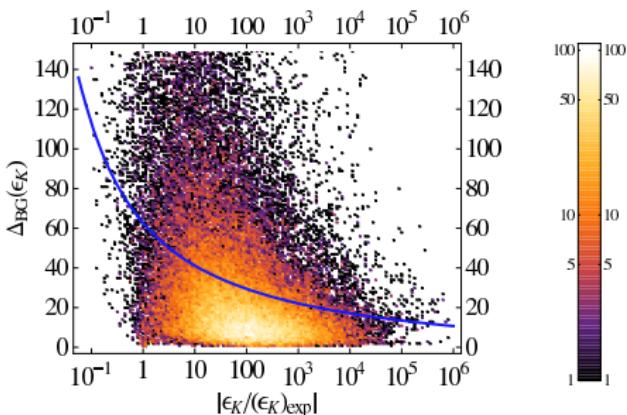
Q_{RR} contribution generally small

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Required Fine-Tuning in ε_K

BBDGW

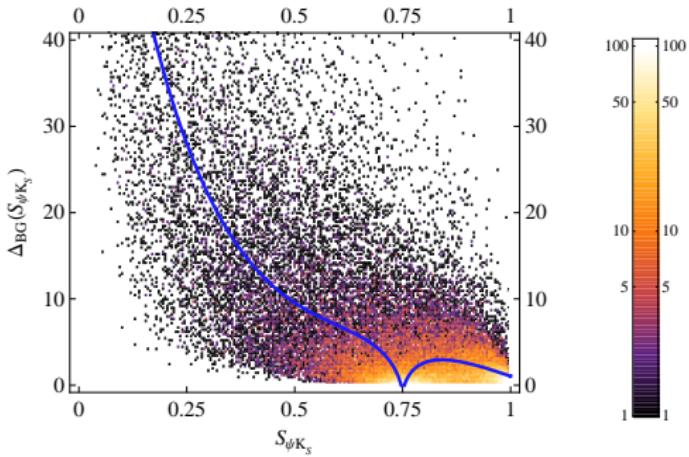
Barbieri-Giudice measure of fine-tuning:
sensitivity of observable to small variation of model parameters



- generically $\varepsilon_K \sim 10^2 (\varepsilon_K)_{\text{exp}}$
- required tuning generically increases with decreasing ε_K
- $\varepsilon_K \sim (\varepsilon_K)_{\text{exp}}$ possible without significant tuning

Situation for other $\Delta F = 2$ Observables: $S_{\psi K_S}$

BBDGW



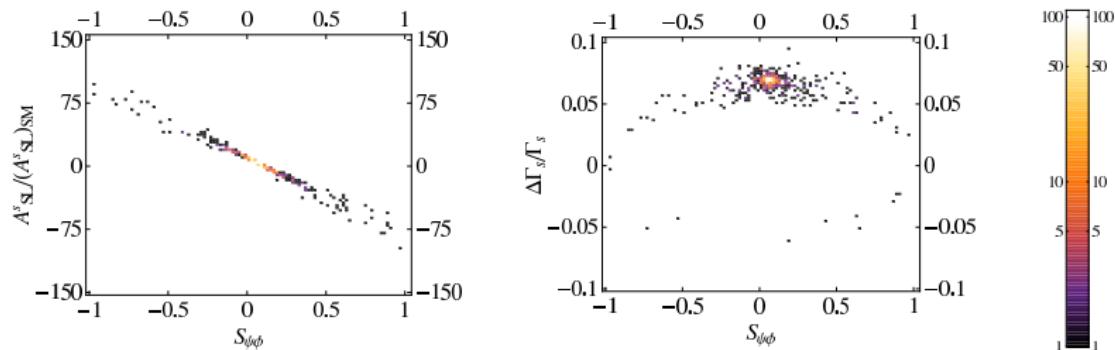
- generically $S_{\psi K_S} \sim (S_{\psi K_S})_{\text{SM}}$ predicted
- **possible tension** between SM and data easily **resolved**

similar situation for other $\Delta F = 2$ observables

CP-Violation in $B_s - \bar{B}_s$ Mixing

after imposing existing $\Delta F = 2$ constraints:

BBDGW



- full range $-1 < S_{\psi\phi} < 1$ possible
→ can explain recent CDF and DØ data
- strong correlation with A_{SL}^s (see LIGETI ET AL., HEP-PH/0604112)
→ $A_{SL}^s / (A_{SL}^s)_{SM} \sim 100$ possible
- $\Delta \Gamma_s / \Gamma_s$ can deviate significantly from SM prediction

Our complete analysis of $\Delta F = 2$ processes in a custodially protected warped extra dimension showed:

- $K - \bar{K}$ dominated by \mathcal{Q}_{LR} , KK gluons
- \mathcal{Q}_{LL} important for $B_{d,s} - \bar{B}_{d,s}$, sizable electroweak KK contributions
- custodial protection for $Z b_L \bar{b}_L$ strongly suppresses flavour violating Z coupling $Z d_L^i \bar{d}_L^j$

Conclusions & Outlook

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- ε_K constraint can be fulfilled without significant tuning
- simultaneous agreement with all $\Delta F = 2$ data can be obtained
- large new physics effects in $S_{\psi\phi}$, A_{SL}^s and $\Delta\Gamma_s$ are possible

Implications for rare K and $B_{d,s}$ decays:

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Implications for rare K and $B_{d,s}$ decays: coming soon!

Back-up slides

Sources of Flavour Violation & Parameter Counting

AGASHE, PEREZ, SONI, HEP-PH/0408134

Flavour is violated by:

• bulk mass terms c_Q, c_u, c_d:	3×6 real parameters
3×3 hermitian matrices	3×3 complex phases
• Yukawa couplings λ_u, λ_d:	2×9 real parameters
3×3 complex matrices	2×9 complex phases
	<hr/>
	36 real parameters
	27 complex phases

$U(3)^3$ flavour symmetry

can be used to remove

- 9 real parameters
- 17 complex phases

physical flavour parameters:

27 real parameters
10 complex phases

RS versus Froggatt-Nielsen

bulk fermions in RS

$$(Y_{u,d}^{\text{WED}})_{ij} \propto (\lambda_{u,d})_{ij} e^{-kL(c_Q^i - c_{u,d}^j)}$$

self-similarity along y

bulk mass parameters $c_{Q,u,d}^i$

IR brane at $y = L$

warp factor e^{-kL}

Froggatt-Nielsen symmetry

$$(Y_{u,d}^{\text{FN}})_{ij} \propto (\lambda_{u,d})_{ij} \epsilon^{a_i - b_j^{u,d}}$$

$U(1)_F$ symmetry

$U(1)_F$ charges $Q_F = a_i, b_i^{u,d}$

VEV of scalar Φ ($Q_F = 1$)

$$\epsilon = \langle \Phi \rangle / \Lambda \ll 1$$

- **geometric interpretation of flavour symmetry**
- FN formulae for masses and flavour mixings can be applied
→ dependence on $\lambda_{u,d}$ and CP phases made explicit

BBDGW; CASAGRANDE ET AL., 0807.4937

Explicit Expressions for Masses and Mixings

quark masses:

$$m_b = \frac{v}{\sqrt{2}} \lambda_{33}^d \mathbf{f}_3^Q \mathbf{f}_3^d$$

$$m_s = \frac{v}{\sqrt{2}} \frac{\lambda_{33}^d \lambda_{22}^d - \lambda_{23}^d \lambda_{32}^d}{\lambda_{33}^d} \mathbf{f}_2^Q \mathbf{f}_2^d$$

$$m_d = \frac{v}{\sqrt{2}} \frac{\det(\lambda^d)}{\lambda_{33}^d \lambda_{22}^d - \lambda_{23}^d \lambda_{32}^d} \mathbf{f}_1^Q \mathbf{f}_1^d$$

flavour mixing matrices (responsible for FCNCs):

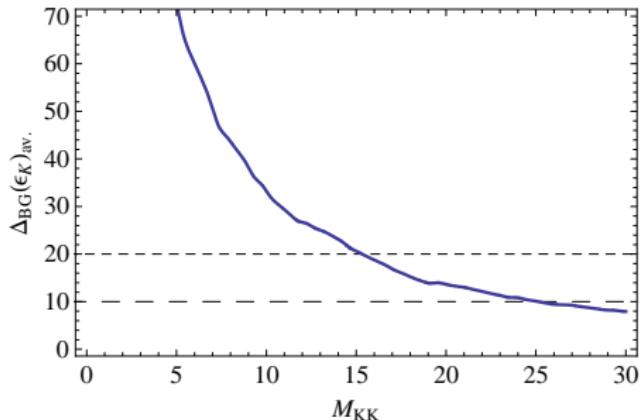
$$(\mathcal{D}_L)_{ij} = \omega_{ij}^d \frac{\mathbf{f}_i^Q}{\mathbf{f}_j^d} \quad (\mathcal{D}_R)_{ij} = \rho_{ij}^d \frac{\mathbf{f}_i^d}{\mathbf{f}_j^d} \quad (i < j)$$

($\omega_{ij}^d, \rho_{ij}^d$: functions of λ_d)

analogous formulae for the up-type quarks

Generic Bound on KK Scale

BBDGW



average required tuning in ϵ_K , depending on M_{KK}

→ generic naturalness bound: $M_{\text{KK}} \simeq 20 \text{ TeV}$